Temporal and Spatio-Temporal Databases

(continuation of Spatial …)

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Possible Applications

- Personnel or medical records
- Reservation systems
- Archaeological records
- Calendars, planning, scheduling, configuration management
- Real-time process monitoring, data streaming

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Breadth of Interest

- According to Zaniolo, et al., 1995:
  - It is hard to find applications that *don't* involve some form of temporal information.
  - Over 40 distinct temporal data models have been defined.

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Temporal Concepts

- Represent time of **events**
- Represent time **intervals**
- Represent **histories** (= mapping from time interval to events or value)
- Represent **periods** of repeating events
- Sometimes only need ***sequences*** of events rather than times themselves:
  - Loosely think of this as "time".

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"Valid-Temporal" Concepts

- Conventional data base:
  - Tuple represents a fact
- Temporal database:
  - Tuple represents a fact that:
    - holds at a specified time (called the ***valid* time**), ***or***
    - holds over an **interval** of time (called an **invariant**) over the interval (which can include the future as well as the past)
    - holds at **some** time during an interval

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Sample Valid-Temporal Queries

- Was Mary the manager of the IT Department during the year 2002?
- Find all managers of the IT Department from 1/1/2000 to 12/31/2003.
- Find out who was promoted during the year 2003.
- What was the configuration of the system on March 12, 2001?

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"Transaction-Temporal"

- Tuple can also show that time at which it was **stored** in the database.
- Note possible connection with multi-version DB.
- "Bi-temporal": both temporal and transaction temporal.
- Ancillary information: Who authorized the change?
- Might also want to show when info **deleted,** when a request to delete was made, etc.

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Transaction-Temporal Queries = Introspective

- Queries that ask questions about changes to the database.
- When was the information that John was promoted to manager inserted?
- When was the fact that John is manager of the sales department deleted?
- When was the configuration of the system changed to include the TeraTuple 2000 disk farm?

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Transaction Time

- Interval representation - **DBMS maintained**

Movie	*Actor*	*Transaction Time start*	*end*
Toy Story	Tom	Jan/4/1999	*now*
Lion King	Mustafa	Jan/4/1999	*now*
True Lies	Arnuld	Jan/4/1999	Jul/1/2000
True Lies	Arnold	Jul/2/2000	*now*

- On Jul/2/2000
  - DELETE FROM Movie WHERE Actor=‘Arnuld’;
  - INSERT INTO Movie (‘True Lies’, ‘Arnold’);
- **Schema evolution** (e.g., Roddick and Snodgrass, *TSQL2*, 1995) Schema itself can change

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Example: Stock Market DB

- Stock price changes throughout session.
- Price has 3 components: **ask** (by seller), **bid** (by buyer), **sold**
- Bid transaction includes amount buying, price, expiration, buyer, broker
- Ask transaction includes amount offered, price, expiration, seller, broker
- Sell transaction includes amount sold, price, buyer, seller, broker
- Other transactions:
  - Cancel transaction
  - Limit order transaction
  - Stop-loss order transaction
- Which are valid-time and which are transaction-time aspects?

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Formal Time Models

- Continuous, Rational, Discrete, or Refinable
- Finite, singly-infinite, doubly-infinite
- Linear or Branching (Non-Determinism)
- Centralized or Distributed
- Qualitative or Quantitative

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Example: TEMPOS

- **T**emporal **E**xtension **M**odels for **P**ersistent **O**bject **S**ervers
- Dumas, et al., University of Grenoble
- Extends the Object Database Management Group's (ODMG) object model by enabling classes to be declared as temporal.
- Values are classified as either:
  - Temporal, or
  - Fleeting (only the most recent value kept)
- Recall that this is a precursor to JDO.
- Extends languages:
  - ODL →Temporal ODL
  - OQL →Temporal OQL
- Was implemented atop O_2 (an OODBMS).

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Formal Modeling

Definition 1 (*data model*). A data model M is as a quadruplet $(\mathsf{D}, \mathsf{Q}, \mathsf{U}, [\![\,]\!]_M)$ composed of a set of database instances D, a set of legal query statements Q, a set of legal update statements U, and an evaluation function $[\![\,]\!]_M$. Given an update statement $\mathsf{u} \in \mathsf{U}$, a query statement $\mathsf{q} \in \mathsf{Q}$ and a database instance $\mathsf{db} \in \mathsf{D}$, $[\![\mathrm{u(db)}]\!]_M$ yields a database instance, and $[\![\mathrm{q(db)}]\!]_M$ yields an instance of some data structure. □

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TEMPOS Time Granularity Modeling

We adopt a discrete, linear and bounded time model in which time is structured in a *multi-granular* way [CR87, WJS95] by means of *time units*. A time unit is a partition of the time line into a set of convex sets: each of the elements of this partition is then seen as an atomic *granule* and every point of the time-line is approximated by the granule which contains it. Thus a time unit defines the precision at which time is observed. The granules of a time unit are numbered by natural integers: the order among these integers defines the notion of succession in time and the distance between them defines the notion of duration.

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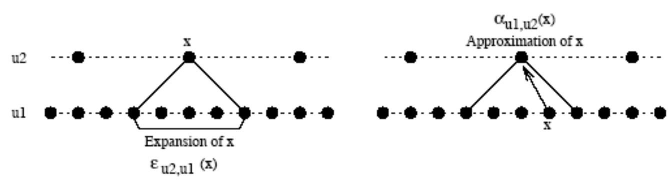
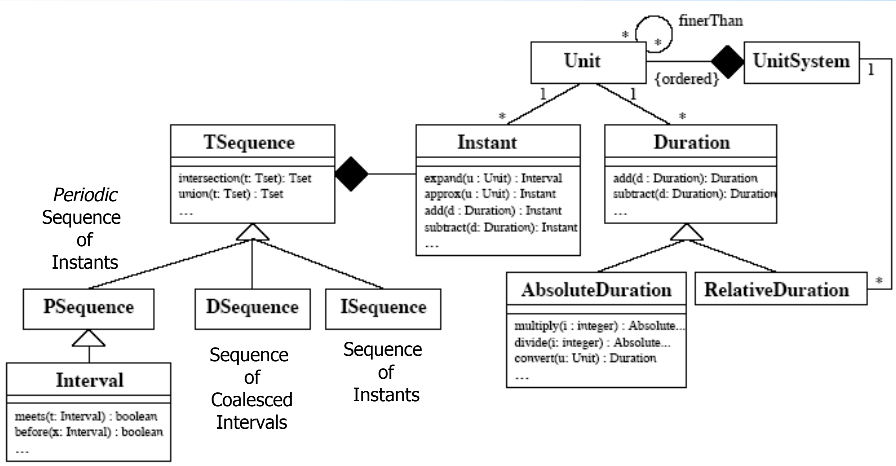
TEMPOS Time Granularity Modeling

For each pair of time units $\langle \mathtt{u1}, \mathtt{u2} \rangle$ such that $\mathtt{u1} \prec \mathtt{u2}$, two conversion functions are defined: one for *expanding* a granule of the coarser unit (u2) into an interval of granules of the finer one (u1) (noted $\epsilon_{u2,u1}$), and the other for *approximating* a granule of u1 by a granule of u2 (noted $\alpha_{u1,u2}$), as shown in figure 1. Units u1 and u2 ($\mathtt{u1} \prec \mathtt{u2}$) are said to be *regular* if the intervals of granules generated by $\epsilon_{u2,u1}$ have all the same cardinality.



Temporal Types Class Diagram

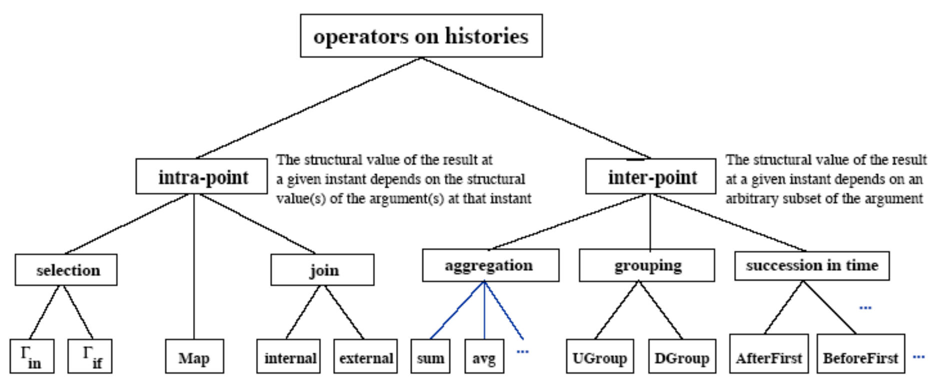


Histories

Histories may be represented in several ways, mainly by means of collections of timestamped values, termed *chronicles*. Among these representations some are useful for query expression, so that specific operators are defined on the History ADT allowing to represent a history in any of these forms. Concretely, a history may be represented by at least three kinds of chronicles:

- Instant-based representation: chronologically ordered sequence of instant-timestamped values, e.g. [⟨1, v1⟩, ⟨2, v1⟩, ⟨4, v1⟩, ⟨5, v2⟩, ⟨6, v2⟩, ⟨7, v2⟩, ⟨8, v3⟩, ⟨9, v1⟩, ⟨10, v1⟩]. Such sequences are termed IChronicles.
- Interval-based representation: chronologically ordered, coalesced sequence of interval-timestamped values, e.g. [⟨[1..2], v1⟩, ⟨[4..4], v1⟩, ⟨[5..7], v2⟩, ⟨[8..8], v3⟩, ⟨[9..10], v1⟩]. This kind of sequence is called an XChronicle.
- Temporal sequence-based representation: set of distinct values timestamped by disjoint temporal sequences, e.g. { ⟨{1, 2, 4, 9, 10}, v1⟩, ⟨{5, 6, 7}, v2⟩, ⟨{ 8 }, v3⟩ }, which are termed DChronicles.

Operators on Histories



Example: Temporal Join

The inner temporal join of two histories ($h1 *_\cap h2$) is a history whose structural values are pairs obtained by combining "synchronous" values of h1 and h2 (i.e. values attached to the same instant). The outer temporal join ($h1 *_\cup h2$), is similar to the corresponding inner temporal join, except that it attaches structural values of the form $\langle v, Nil\rangle$ or $\langle Nil, v\rangle$, to those instants where one of the argument histories is defined while the other is not. Here, Nil denotes the neutral element of the structural domain type (e.g. 0 for integers, nil for objects, etc.). More precisely:

$\_ *_\cap \_$: History<T1>, History<T2> $\rightarrow$ History<$\langle$T1,T2$\rangle$>

/* $h1 *_\cap h2 = \{\langle I, \langle v1, v2\rangle\rangle \mid \langle I, v1\rangle \in h1 \wedge \langle I, v2\rangle \in h2\}$ */

/* *precondition: Unit(h1) = Unit(h2)* */

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Temporal Join Example

(from Zaniolo, et al. 1995)

- Employee1:

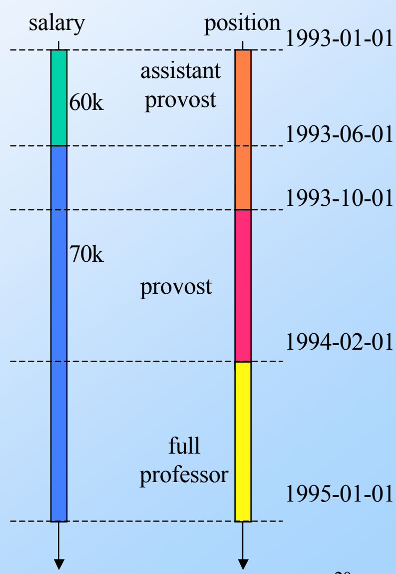
Name	Salary	Start	Stop
Bob	60000	1993-01-01	1993-06-01
Bob	70000	1993-06-01	1995-01-01

- Employee2:

Name	Title	Start	Stop
Bob	Assistant Provost	1993-01-01	1993-10-01
Bob	Provost	1993-10-01	1994-02-01
Bob	Full Professor	1994-02-01	1995-01-01

- Result of temporal join:

Name	Salary	Title	Start	Stop
Bob	60000	Assistant Provost	1993-01-01	1993-06-01
Bob	70000	Assistant Provost	1993-06-01	1993-10-01
Bob	70000	Provost	1993-10-01	1994-02-01
Bob	70000	Full Professor	1994-02-01	1995-01-01



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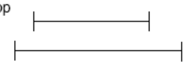
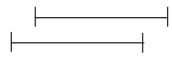
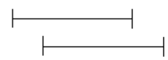
Temporal Join in Plain SQL

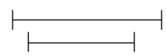
(from Zaniolo, et al. 1995)

```
SELECT Employee1.Name, Salary, Title,
                Employee1.Start, Employee1.Stop
FROM Employee1, Employee2
WHERE Employee1.Name = Employee2.Name
    AND Employee2.Start <= Employee1.Start
    AND Employee1.Stop <= Employee2.Stop
UNION ALL
SELECT Employee1.Name, Salary, Title,
                Employee1.Start, Employee2.Stop
FROM Employee1, Employee2
WHERE Employee1.Name = Employee2.Name
    AND Employee1.Start > Employee2.Start
    AND Employee2.Stop < Employee1.Stop
    AND Employee1.Start < Employee2.Stop
UNION ALL
SELECT Employee1.Name, Salary, Title
                Employee2.Start, Employee1.Stop
FROM Employee1, Employee2
WHERE Employee1.Name = Employee2.Name
     AND Employee2.Start > Employee1.Start
     AND Employee1.Stop <= Employee2.Stop
     AND Employee2.Start < Employee1.Stop
UNION ALL
SELECT Employee1.Name, Salary, Title
                Employee2.Start, Employee2.Stop
FROM Employee1, Employee2
WHERE Employee1.Name = Employee2 Name
     AND Employee2.Start => Employee1.Start
     AND Employee2.Stop <= Employee1.Stop
     AND NOT (Employee1.Start = Employee2.Start
          AND Employee1.Stop = Employee2.Stop)
```









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Temporal Join in TSQL2

(from Zaniolo, et al. 1995)

```
SELECT Employee1.Name, Salary, Title
FROM Employee1, Employee2
WHERE Employee1.Name = Employee2.Name
```

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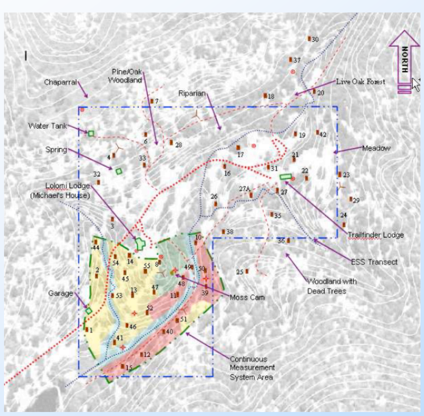
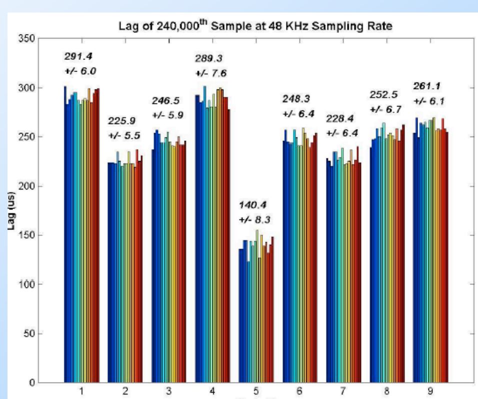
Example Spatio-Temporal Applications

- Record the historical evolution of a landform (such as a volcanic region, or global earthquakes)
- Understand weather data, or flow of groundwater and contaminants
- Chart the propagation of spoken or written languages
- Trace the migration of a population of animals
- Anticipate the spread of an epidemic
- MRI or PET imaging
- Track terrorists
- Choreography, any motion picture or animation, video games

A well-sampling application that uses wireless sensor networks (Ganeson, et al., UCLA)





General Desiderata for Spatio-Temporal Models

- Should be upward compatible from classical methods (i.e. should subsume them)
- Deal with interactions of time and space, not just the two independently (e.g. space-time constraints)
- Expressive, yet easy to use
- Compatible with existing frameworks

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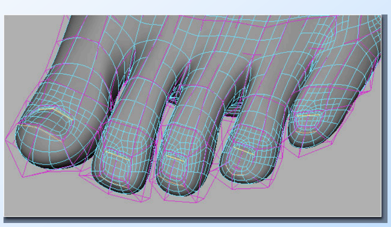
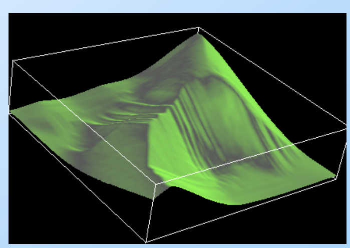
Possible Test-beds

- Any of a variety of 3D modeling tools, such as Maya, AutoCAD, GeoToolKit





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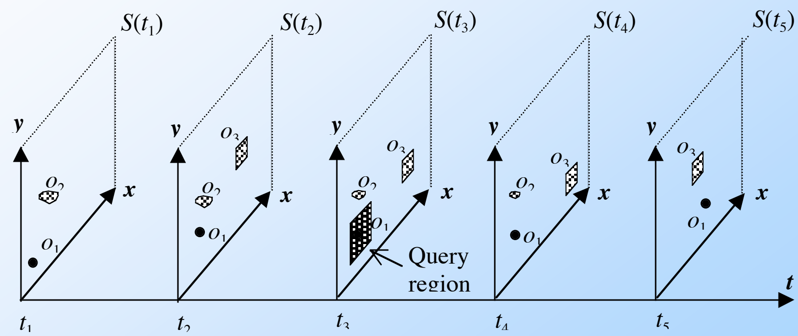
Spatio-temporal Evolution



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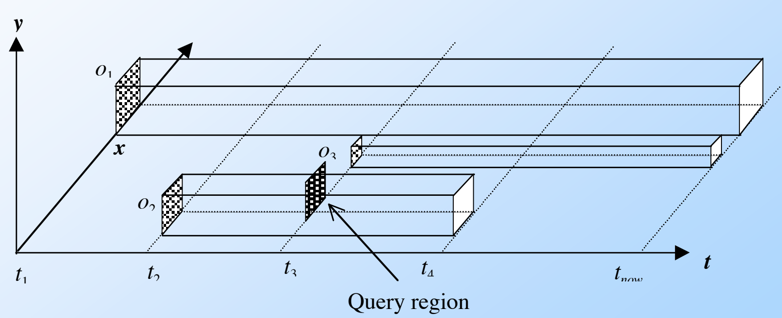
Indexing using R-trees

- Assume that time is another dimension, use a 3D R-tree



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Additional Directions

- Constraint Logic Programming
- Machine learning
- Data mining

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Assertion: The WWW is a Database

- What aspects are:
  - relational?
  - object-oriented?
  - temporal?

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Query Language

- URL is, in effect, a primitive query
  - identifies single, whole document as the answer
- Some information exists, but cannot be queried
  - Requires natural language text understanding

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Other Ways to Access Data over WWW

- CGI/HTTP
- Applets
- Servlets (= server-side applets)
- .NET

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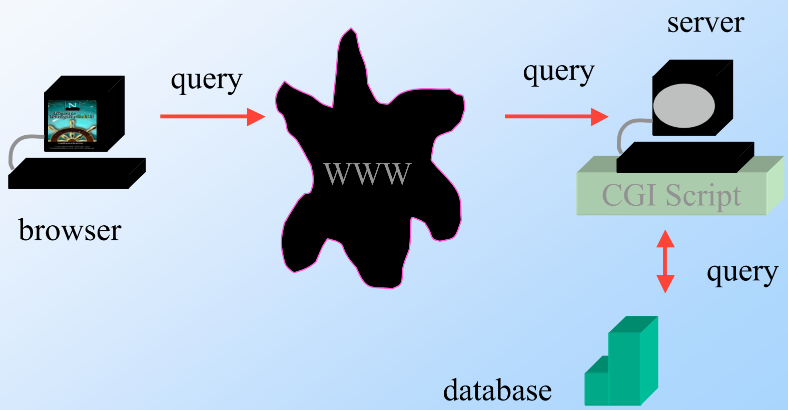
HTTP (CGI) Gateway



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HTTP (CGI) Gateway

- HTML forms, limited GUI
- result formatting
- HTTP/database protocol mismatch
  - "stateless" protocol
  - single query transactions

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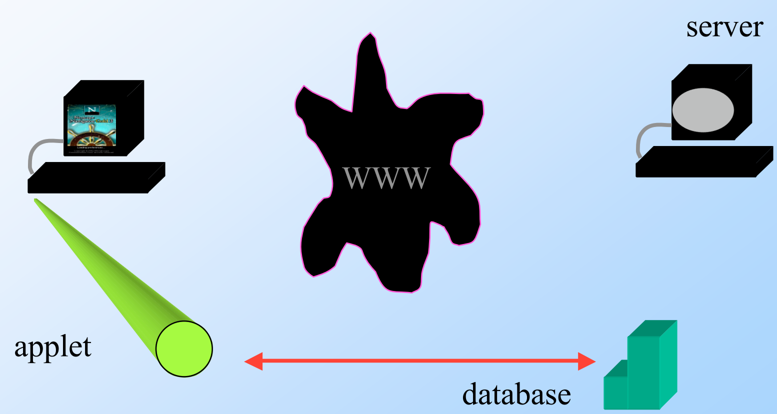
Java Applets



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Java Applet

- "stateful"
- fancy GUI
- robust, secure, platform-independent
- database API - JDBC

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WWW Data Structure

- WWW is data repository
- unstructured (semi-structured)
  - HTML tags
  - XML tags
  - WWW graph (graph of hyperlinks)
- primitive query
  - URL identifies single, whole document

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Consistency

- redundant information
  - plenty of it: hardly normalized
- incorrect information
  - 5% of links are broken
  - little certification, if any
- triggers/assertions/constraints
  - guarantee consistency

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An Issue for Investigation

- Does the WWW support transaction-time temporality? If not, can it be extended to do so?

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